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LUNAR STUDIES

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I. INTRODUCTION

Our research has continued to progress in the past six months both in the experimental and theoretical areas.

The continuation of the experimental investigation of the optical and related chemical properties of lunar material has been one of our major concerns. The analysis of the chemical composition by Auger electron spectrometry of the surface of lunar dust and ground-up rock samples has been continued, along with the measurement of the albedo of these samples. Results are now available for a great variety of dust and rock samples and the correlation, found earlier, between the iron concentration on the surface of grains and their albedo has been fully confirmed.

In the past few months our experimental work has been concentrated on solar wind simulation experiments directed toward the understanding of (1) the importance of the role of the solar wind in darkening the regolith and (2) the mechanism of such a process.

It has been established that the solar wind is most likely to be a major factor in the darkening process; more experiments are needed for the understanding of the darkening mechanism. In the course of the various solar wind simulation experiments, a number of modifications were carried out on the ion bombardment system which will remove some uncertainties due to surface charging effects.

Very considerable progress has been made in our theoretical research on the interpretation of the lunar soil cosmic ray track density data and other surface exposure effects.

Excavation and redistribution of lunar soil by meteorites was modelled in 3-dimensional fashion in a new Monte-Carlo computer calculation. The results confirm the indications of our preliminary, one-dimensional calculation--exposure in situ, with meteorites bringing material to the surface, cannot account for the notable extent to which unexposed grains are absent. A wide range of cases (involving different median depths of tilling and penetration curves for solar and galactic cosmic rays) was investigated; all resulted in too high a percentage of grains with less than a thousandth the mean grain track density. Under random bombardment, admixture of fresh material from beneath continually spoils what might otherwise have been a distribution with no unexposed grains. The new calculation shows that this is true despite the enhanced exposure to cosmic rays which the thinness of crater ejecta blankets provides. (Because of covering by ejecta from other craters, ejecta blankets too frequently fail to receive a significant amount of further exposure.)

The indications of the study are that accretion of pre-exposed material from space and/or from other areas of the lunar surface is necessitated. Receipt of pre-exposed material would also help explain the large total amount of cosmic-ray exposure which the lunar regolith exhibits. (Grains in the upper 3 meters show an average track density of $\gtrsim 1 \times 10^7$ tracks/cm^2.) The high mean level of exposure is yet more of a problem if the regolith had its origin in the comminution of lava beds. The regolith would have to have been tilled to its full depth (more than some tens of meters, judging from the radar evidence, and much more on the basis of the seismic evidence). In the case of such thorough working, the material beneath the depths sampled is likely to have received exposure also, increasing the required total fluxes both of cosmic rays and solar wind to extraordinarily high values. At the same time, the problem of the low fraction of unexposed grains, and the well-defined layering in core samples, would be unaccounted for. This suggests strongly that we are dealing with accreted material that had suffered much of its exposure before falling onto the Moon,

We are in the process of performing further calculations which will make possible the inclusion of additional terms in the sums of the statistical compounding process. Inclusion of the additional terms will reduce the extent to which the 3-dimensional calculation underestimates the fraction of grains which receive negligible exposure. The new calculations will also provide the details of the high-exposure end of the statistical distributions.

II. EXPERIMENTAL RESEARCH

A. Auger Analysis of Lunar Samples

In addition to the data presented in the last report, Auger spectra were obtained of numerous lunar dust and ground-up rock samples; the albedo of all these samples was also determined. Figure 1 summarizes the results. It is clear from this graph that whereas the bulk iron concentration and the surface iron concentration is similar in cases of ground-up rock samples, all the dust samples are enriched in iron on the surface of the grains. Correspondingly, the dust samples are darker than the ground-up rock of similar bulk iron concentration. Some of the rocks analyzed recently, such as rock 10062 and 10057, have a remarkably low albedo. These rocks are not only rich in iron but also in titanium, both elements contributing to their dark color. In recent sample allocations we obtained a number of both rock and dust samples with relatively high titanium content; thus we were able to compare the bulk titanium content to the surface (Auger) titanium concentration in these samples. Although titanium is only present in a maximum concentration of a few atomic percent in the samples we examined and therefore our Auger results are less definite than for iron (the Ti peak, in some cases, being barely above noise level), we were able to determine that titanium also is enriched on the surface of dust grains. The average titanium enrichment is less than two fold, and thus less than the iron enrichment. This is not unexpected in the case of a solar wind caused sputtering process on the basis of different sputtering rates and sticking coefficients for different elements. Whatever is the governing factor in the sputtering process, the enrichment is expected to be generally increasing with atomic mass. Titanium is much less abundant than iron in all lunar rocks investigated, and this, together with its tendency to be concentrated less on the surface, indicates that iron is likely to be much more important in influencing the optical properties of dust than titanium, and the relationship found earlier between surface iron concentration and albedo presumably holds also for titanium-rich dust samples. In Figure 2 the bulk iron concentration, the surface iron concentration and the iron concentration required to cause the observed albedo (according to a theoretical law) were plotted for all the dust samples we have examined. This law is of the form $A=A_0e^{-n\sigma}$, expected for an absorption center density proportional to the measured iron concentration. The iron concentration required to cause the observed albedo was calculated by a least square fit of the albedo (A) and the measured surface iron concentration (n) to this law. As Figure 2 indicates, the measured iron concentration fits this law very closely for all iron-rich samples but indeed does not in the case of iron-poor, light soil samples, where presumably the albedo is dominated by other effects.

B. Solar Wind Simulation Experiments

Results of preliminary experiments were reported in our last report. These results showed that the Auger spectrum of a ground-up lunar rock sample, exhibiting very small iron peaks, changed markedly after irradiating the sample with a 2 keV energy proton dose corresponding to 8000 years of solar wind. The Auger spectrum of the proton irradiated rock powder showed approximately three times larger iron peaks than the irradiated material and it was very similar to the spectrum of lunar dust collected at the same location as the rock. The albedo of the rock powder as expected became lower as the result of the irradiation. No increase of carbon concentration was observed on the surface of the irradiated powder; therefore the darkening as a result of contamination can be excluded. We have thus demonstrated that simulated solar wind not only darkens rock powders (as observed by Hapke earlier) but also changes the surface chemistry to a similar composition to that of the lunar soil. Proton and α particle irradiation experiments were repeated on several other ground rock samples. Auger analysis of these samples was performed before and after irradiation. The tabulated results of these experiments will be published shortly.

Much effort was spent these past few months on the elucidation of the sputtering mechanism. In one series of experiments a gold foil was placed above part of the ion bombarded target in order to collect sputtered-off material from the latter. In some experiments we used an alumina substrate for the same purpose. We found that the Auger spectrum of the sputter deposited film on the substrate, as compared to that of the unirradiated target material, showed enrichment in oxygen and in the light elements. On the other hand, the iron/oxygen ratio on the film was one-half (or less) of this ratio on the surface of the target material. These experiments were repeated with different irradiation doses from 2.5 to 10 coulombs/cm^2 of 2keV protons without changing the results markedly. The above observation seems to indicate that the sputter deposited film is enriched in elements with higher sputtering rates, whereas those with lower sputtering rates are enriched on the target surface. In this case the sputtering rate would be the determining factor in changing the chemistry of the surface. This observation appears to be in disagreement with that of Cassidy and Hapke (1). They performed similar irradiation experiments with lunar-like glass targets and molybdenum substrates and determined the chemical composition of the sputter deposited film on the substrate and of the target by electron microprobe analysis. Heavy elements were found to be systematically enriched in the film, indicating that the heavier the sputtered atom, the greater its tendency to stick to the first surface it strikes. According to this result, it is the sticking coefficient of an element which plays the most important role in the sputtering process and determines in what ratios the sputtered-off atoms will redeposit. Lunar soil grains would get enriched in heavy elements by differential deposition of atoms sputtered off by the solar wind.

Another series of experiments was designed for the comparison of the chemical composition of those grain surfaces which were directly exposed to proton bombardment to the composition of the unexposed side of the grains. This was achieved by irradiating powder samples with the ion beam hitting the surface at various angles and analyzing this surface with the Auger electron beam directed also at various angles to the surface.

Experimental difficulties, however, have prevented us from reaching really meaningful results so far. Some modifications on the ion bombardment chamber were made necessary. Although these experiments seem to be somewhat difficult to perform, we feel that the results might contribute significantly to the elucidation of the sputtering process.

Our Auger spectrometer will become more versatile in the near future, thanks to the cylindrical mirror analyzer delivered by Varian. We intend to incorporate the new analyzer into the spectrometer as soon as our current series of experiments is successful.

III. THEORETICAL RESEARCH

A. Regolith Cratering and Exposure

Our recent work on this subject has centered around a new 3-dimensional calculation of regolith exposure. (Our earlier study (3) modelled the situation in 1-dimensional fashion.) Excavation and mixing of the soil according to the cratering frequency law of Shoemaker *et al.* (2) was employed, as previously. The results confirm the indications of the provisional study--too high a fraction of the grains of an average sample escape galactic cosmic rays and solar wind exposure. (The observed fraction of grains showing no exposure is of the order of or less than 1%--(5).) The conclusions of the study are not very sensitive to the crater production law assumed. Typical results of the study are shown in Figure 3. The severe difficulties remain no matter how deeply or shallowly meteorites have tilled the soil--thorough tilling inevitably admixes unprocessed material from beneath, and any smaller amount of meteoritic working of the soil provides insufficient chance for residence within an exposure depth beneath the surface. Admixture of previously unprocessed material from beneath is unavoidable in the actual case and was artifically excluded in the theoretical simulation to less an extent than in the calculations of others (e.g., (4)). A paper discussing the statistics of degree of exposure was presented at the Conference on the Interactions of the Interplanetary Plasma with the Modern and Ancient Moon (October 1974). The implication of the statistics is that pre-exposure in space and/or during transit by some orderly process from the uplands is required for the bulk of the lunar soil. Electrostatic transport of grains across the lunar surface (see, for example, (6),(7)) and above-surface transport (8,9) of individual grains are examples of lunar surface processes which would assure that each grain deposited had received at least some exposure.

Work is being continued on the relation between probability of exposure of grains in lunar soil samples and the degree of eradication of any initial vertical inhomogeneities. The results show that a great degree of homogenization would have been brought about if the regolith were mixed sufficiently in such fashion as to give the observed charged-particle track density distributions. The results indicate that some variety of accretional process is necessary in order to retain the degree of differences observed among layers in lunar soil cores. Accretion from space and/or by orderly transport from distant areas would also provide an explanation for the initial existence of the vertical inhomogeneities.

The theoretical investigation is being expanded to other aspects of the statistics of exposure. A major point which is receiving attention is the relation between the fraction of grains which were exposed one or more times at the surface and the fraction of surface-exposed grains which show signs of such exposure on only one side. Here too, there seems to be a conflict between observations and what one would expect from random "gardening" of the soil by meteorites. In order for the observed fraction of the lunar soil grains to have received exposure at the surface, there would be a certain significant probability of multiple exposure. The latter would limit the fraction of the grains which experienced exposure in only one orientation. The statistics with regard to this are being investigated in order to determine whether impact annealing of one side of grains is necessary in order to explain the observations. The latter would have implications concerning lateral diffusion and the source of the lunar material.

B. Annealing, Melting, and Fracture of Impacting Grains and their Implications Concerning the History of the Lunar Surface Material.

Work has been proceeding on the subject of the heating and shock which small solid particles would experience in coming to rest at the end of a ballistic trajectory. One aim is to be able to use damage features (fracture, spallation, surface melting) as diagnostics of the nature of the event causing the damage. (Determination of the distribution of velocities of impact would be quite useful. It would shed light on the scope of lateral mixing on the Moon. Similarly, velocities in excess of the speed of escape would suggest an extra-lunar source.) In addition, one would like to know whether differential annealing could provide an explanation for the charged-particle track density typically being significantly higher on one side of lunar grains than on the opposite side of the grain. (The possibility of a grain size dependence of heating to track-annealing temperatures is also being investigated.)

We examined the glass beads which constitute the lunar "orange soil" sample and found that they provide evidence of the correctness of the conclusion that smaller particles should experience intense heating (to the melting point) less frequently than larger particles for a given impact velocity. Beads several hundred microns in diameter frequently exhibit patches or sides which are glazed, disrupted, or ablated. The nature of the damage to the otherwise perfect surface makes clear that localized melting and plastic flow occurred. (The spherical beads show such a lack of distortion from sphericity as to rule out that the bead as a whole was still in a plastic state at the time of impact; although the beads presumably originated from a melt, they apparently cooled to the state of a strong solid before impact.) The smaller beads (e.g., of $\sim$50 micron diameter) failed to exhibit such melted patches.

We also have been studying the dependence of the occurrence of impact fracturing, chipping, and heating upon the impact velocity. If the impact velocity is less than the speed of sound in the solid, there is the chance of a shock wave passing through the impacting body so as to reverse the velocity of its far side. Accordingly, a comparatively elastic collision can occur--the grain might rebound or be deflected, giving up some of its momentum to whatever it hit, but possibly not experiencing much crushing, breakage, or conversion of kinetic into thermal energy. For impact velocities in excess of the speed of sound in the solid, an inelastic collision seems assured. We are in the process of setting up an experiment to elucidate the extent of the damage which can occur at impact velocities less than the sonic speed. The lunar case almost never involves collisions against an immovable, hard surface, but rather against a loose collection of free, individual grains, making the situation somewhat awkward to treat theoretically. Accordingly, we will include the latter among the cases investigated experimentally.

Our studies of the "orange soil" samples established that the glass beads exhibit an astatistically high prevalence of a single spot of damage rather than none or several such spots; a random distribution of damage with the same mean value would have exhibited a much larger spread. We examined a total of several hundred beads (the entirety of several small portions of the sample). The observed statistics make clear that the beads received damage primarily by an orderly process. Although the details are not yet clear, the only imaginable process of such a sort entails infall of each bead. We recently have measured the static crushing strength of the lunar glass beads and have made tentative theoretical extrapolations to the kinetic case. The indications are that an infall velocity in excess of the speed of sound in the glass beads may be required in order to produce the observed damage. (The latter would argue for the possibility of an extra-lunar origin for the glass beads, which would be very interesting in view of their having the same bulk composition as much of the lunar surface material.) The experiment being prepared involves impelling glass beads of size and static crushing strength similar to that of the lunar beads against various targets at various velocities up to perhaps two kilometers per second. We hope that it will set reasonably stringent bounds on what the impact velocity of the lunar glass beads must have been.

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FIGURE CAPTIONS

Figure 1: Comparison of the bulk iron content; the surface iron concentration, calculated from the Auger Fe and O peak ratios and normalized with respect to the bulk iron concentration of rock sample 60017; and light absorption in rock and soil samples. Light absorption is 100%-albedo. The albedo was measured as $\lambda = 5500\text{Å}$ at 8° illumination angle and was normalized to MgO.

Figure 2: Similar to the soil sample plot of Figure 1, except that the light absorption column has been replaced by a column representing the surface iron concentration required to cause the observed albedo, if the absorption law of Figure 3 is obeyed. The absorption center concentration n is given by $A = A_o d^{-n\sigma}$, where A is the observed albedo, A_o=0.288 and $\sigma = 0.113$. (Albedo is here expressed as a decimal fraction.)

Figure 3: Model. Cratering events throw out blankets of ejecta.

Figure 4: Time spent within a cosmic-ray exposure depth is recorded. A large number of unexposed grains is seen to result.

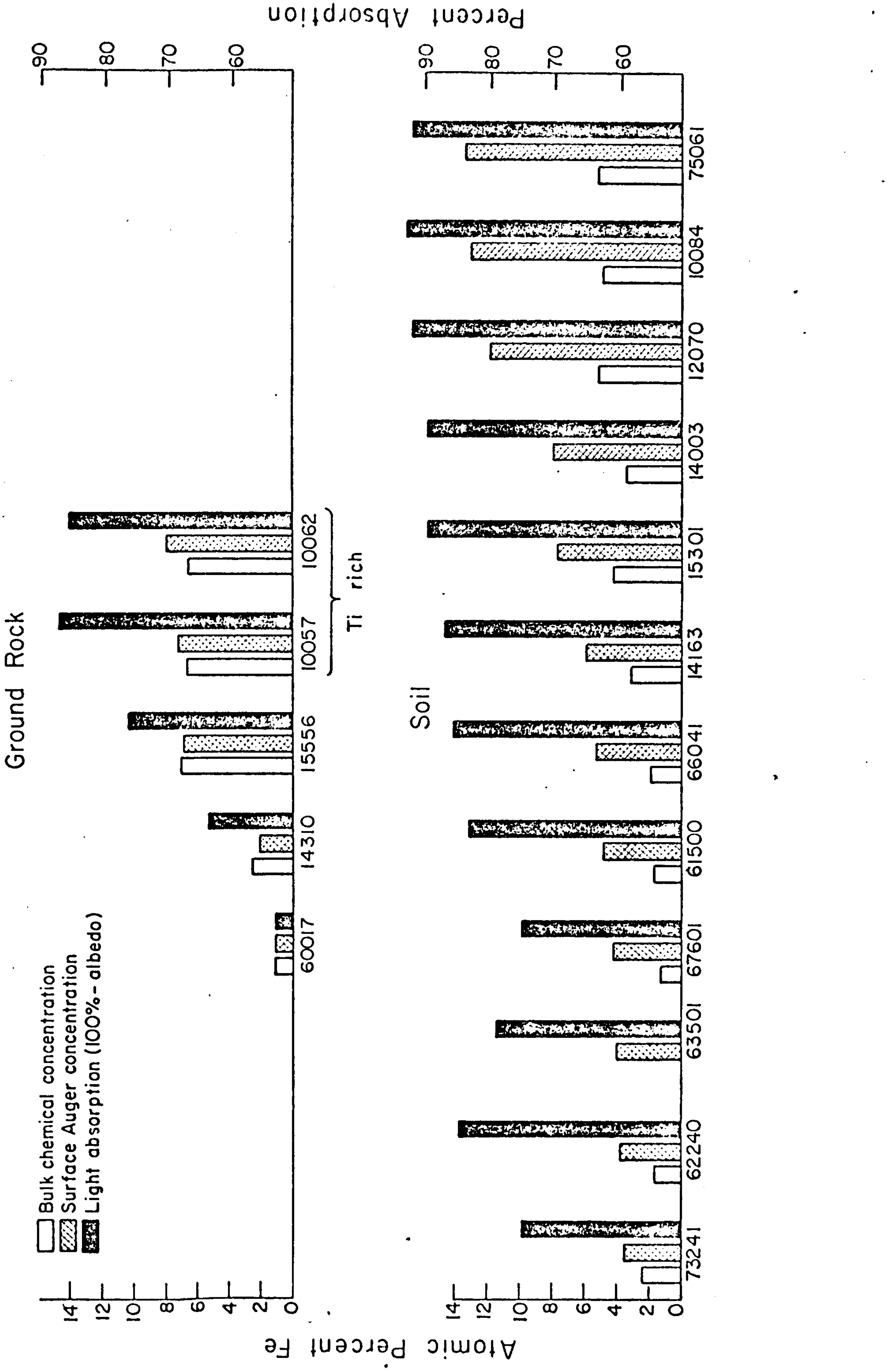
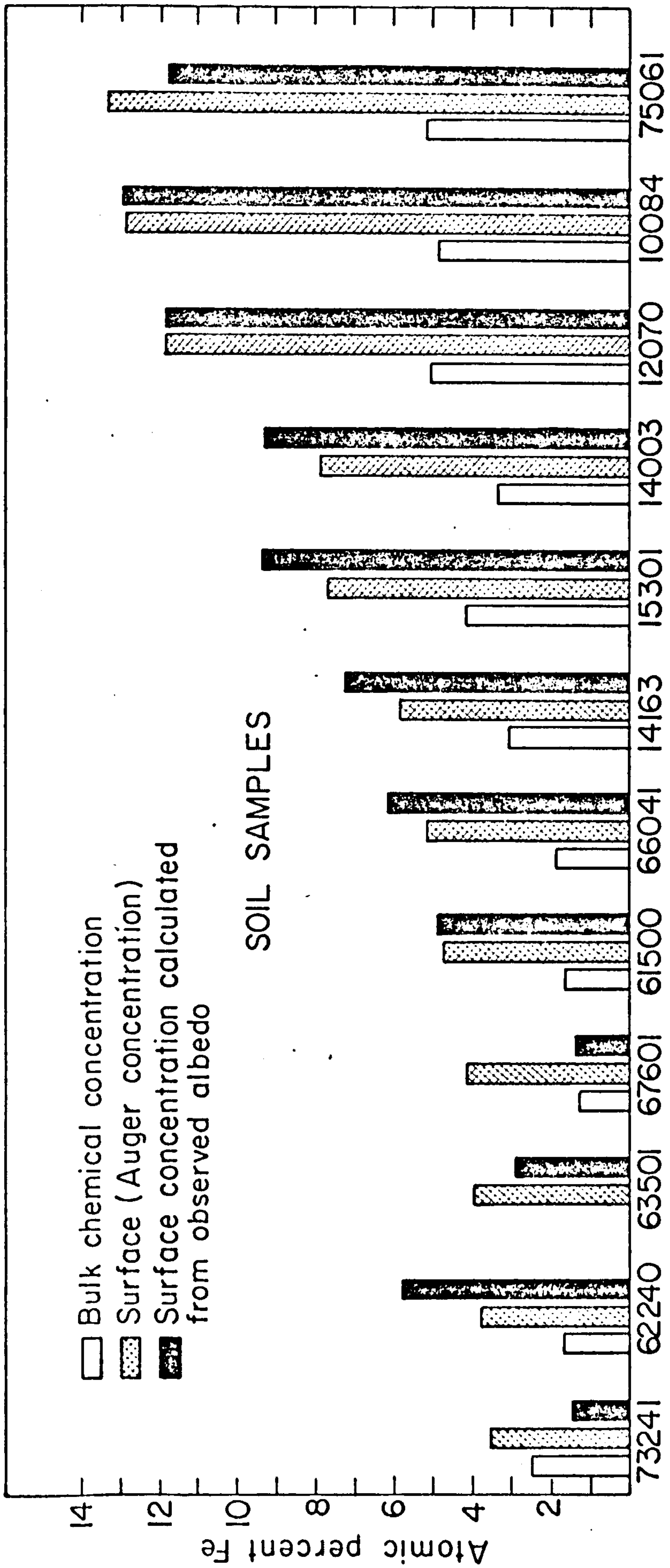

Percent Absorption
Atomic Percent Fe
Ground Rock
Soil
Bulk chemical concentration
Surface Auger concentration
Light absorption (100%- albedo)
60017
14310
15556
10057
10062
Ti rich
73241
62240
63501
67601
61500
66041
14163
15301
14003
12070
10084
75061
90
80
70
60
14
12
10
8
6
4
2
0

Figure 1



Atomic percent Fe
14
12
10
8
6
4
2
Bulk chemical concentration
Surface (Auger concentration)
Surface concentration calculated from observed albedo
SOIL SAMPLES
73241
62240
63501
67601
61500
66041
14163
15301
14003
12070
10084
75061

Figure 2

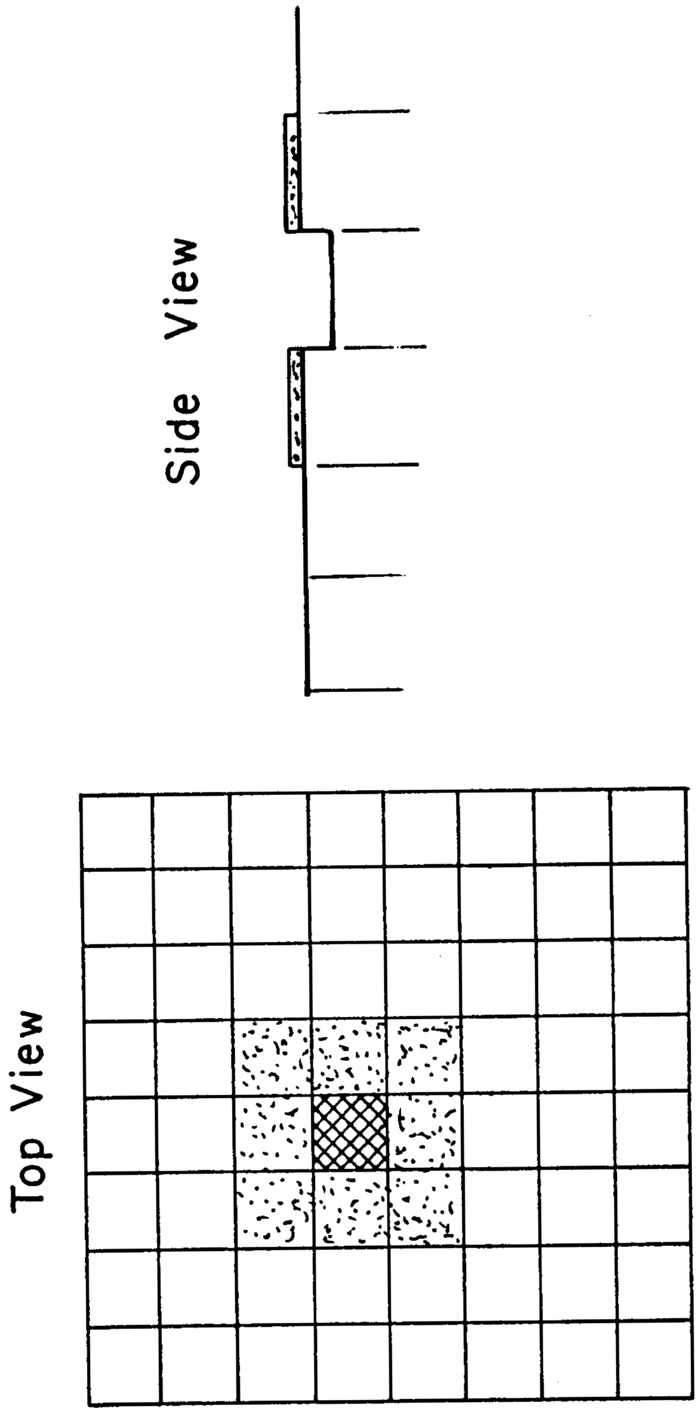


Figure 3

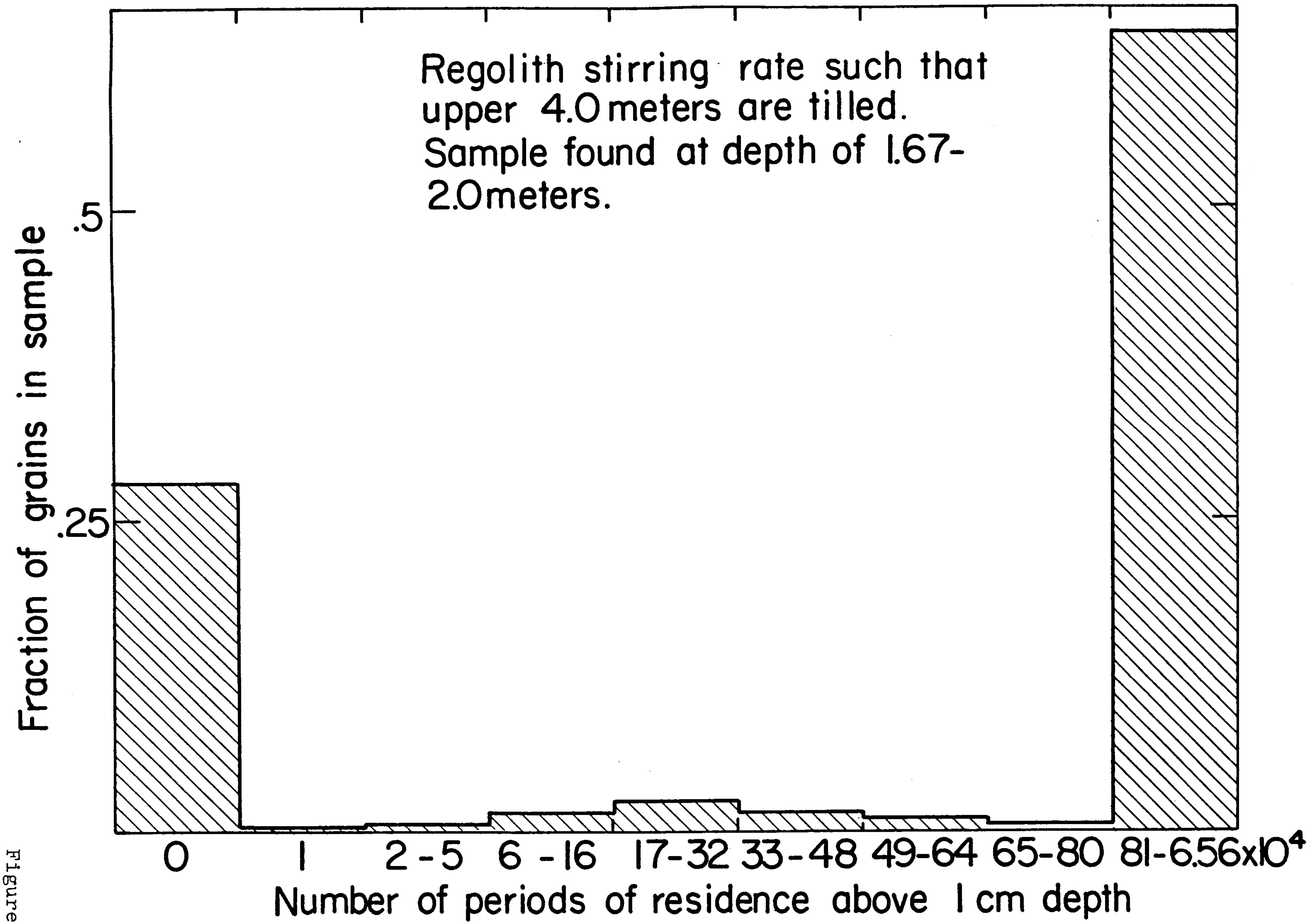

Regolith stirring rate such that upper 4.0 meters are tilled. Sample found at depth of 1.67-2.0 meters.
.5
.25
Fraction of grains in sample
0
1
2-5
6-16
17-32
33-48
49-64
65-80
81-6.56x10⁴
Number of periods of residence above 1 cm depth

Figure 1